THE APPLICATION OF METEOROLOGY TO HYDROLOGIC PROBLEMS.

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(Address by Willis Ray Gregg, Chief, Weather Bureau, before the Society of American Military Engineers, Monday, February 15, 1937.)

The relationships between meteorology and hydrology are many and close. If we include oceanography we have a complete and never ending cycle of the motion of water, wherein it condenses into clouds, is precipitated as rain or snow, flows over and through the earth's crust, accumulates largely in oceans, is taken into the air again by evaporation and transpiration, is again condensed into clouds and precipitated, etc., etc.

The relationships between meteorology and hydrology may be considered under two general headings, namely, statistical data, useful in determining long-period trends, and current information, of great and in fact vital importance in connection with the occurrence of disastrous floods, such, for example, as those in March 1936 and January 1937.

Taking up the statistical side first, the data that are accumulated over a period of years are of tremendous value in connection with many activities, one of the most important being engineering. In this field, as in many others, effort is very properly being concentrated on securing maximum returns consistent with such factors as maximum safety and minimum cost. It is well known that many engineering projects could be so constructed as to be imperishable, short of a cataclysm, but the sponsors would be rendered forever bankrupt. We should be prepared to spend enough but not to waste. We must avoid both overdesign and underdesign. Special emphasis is placed on this thesis in a report issued in September 1936 by the National Resources Committee under the title "Deficiencies in Basic Hydrologic Data."

Necessarily, the longer the period of observation the more definite the conclusions that can be drawn. It is well known that rainfall for example seems to be roughly cyclic in character, and it is essential therefore that we have records from individual stations that cover periods as long as possible, in order to extend over several of these cycles and thus provide adequate information as a basis for long range forecasting. In this case I use that term without specification as to time. This is a perfectly proper use of the term, as it enables us to tell quite definitely what are likely to be the <u>extremes</u> in precipitation or any other element over a long period of time. On such information can be based conclusions as to available supplies of water from mountain snows or from rains for irrigation, power, and for the ordinary needs of cities. It must be emphasized that as yet we have no records which are of sufficient length to give this information completely, and it is necessary, therefore, in any engineering project to include a fairly liberal factor of safety. This is one among many reasons why we are putting forth every possible effort to secure funds for improving and expanding the statistical branch of the service.

The other phase of relationship between meteorology and hydrology is concerned with the collection of current information and the issuing of forecasts of river stages based thereon.

Flood forecasting on a systematic basis seems to have had its beginning in France in 1854. The extent of the network of stations used is not known, nor

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is it clear, from the literature available to us, what degree of success was attained in making the predictions. However, the obstacles that undoubtedly were in the way were overcome, for the flood forecasting service in France has not been interrupted since its beginning, 83 years ago. Similar work was undertaken in Italy and Bohemia about 1866, and in the United States in 1871, the latter date being one year after the establishment of the national weather service.

Flood forecasting as practised by the Weather Bureau now is divided into two general divisions, differing radically in the methods employed in reaching conclusions as to the stages to be expected. The older and more refined method is forecasting from gage relations and (in the last few years) from discharge data. The second is forecasting largely or altogether from reports of rain that has fallen or is expected to fall.

In forecasting from gage relations and from discharge data intervening rains must be given weight, but the underlying factors are up-river stages. It undoubtedly is a truism, and it may seem unnecessary to say, that the farther a reach is from its source-water the greater the time-range that is possible in making a flood forecast, but the statement is made to bring out more forcefully the difference in the two general divisions of forecasting. On the larger streams or the reach of any stream several days removed from the regions of the flood producing rains, there is sufficient time to make the final forecast in refined terms, both as to stage and as to time. This is done now in a satisfactory way and has been done for some 65 years. The term of the forecasts ranges from 2 to 3 days in the upper valleys to as much as 3 or 4 weeks in the lower Mississippi Basin.

As a rule, it is impracticable to use gage relation or discharge data in making flood forecasts for regions into which flow numerous small streams, which may be considered source-water streams. These numerous headwater or source-water streams, and the channels that are water carriers only during heavy rains, cannot be gaged in a way that would make the observations valuable in flood forecasting. The channels are too numerous and gaging them is not economically practicable, even though it might be possible in some cases. Therefore, it becomes necessary to rely upon reports from rain gage stations placed in the catchment basins in a way that will give the forecaster a clear and current knowledge of the amount and intensity of the rain, and its geographic distribution. In much of the country east of the Appalachian Mountains flood forecasts to be timely enough to be of real benefit must be made from rainfall reports.

This last statement was strikingly illustrated in the floods of March 1936. Practically all of the rivers involved were comparatively small ones and the time between the fall of the heavy rains and the occurrence of flood stages was very short. It was impossible to make forecasts on the basis of stages in the upper parts of these small rivers.

The floods of January 1937, still continuing, illustrate the application of both approaches to the problem of flood forecasting. The forecasts for the Mississippi, for example, that are now being made are almost entirely on the basis of the up-stream stages. Those in the Ohio on the other hand were in considerable part based on the occurrence of the heavy rain that prevailed for the greater part of the month on ground that was already saturated.

The prelude to the record breaking floods in the Ohio Valley during

January 1937 was a gradual building up of conditions favorable to producing maximum floods. There was abundant precipitation, ranging from near normal to considerably above normal, rather generally east of the Great Plains. Thus, at the beginning of January, the ground was in a well saturated condition allowing a high percentage of run-off from any further rain that might fall. Also, the Ohio River and its tributaries began a slow rise at the close of December due to the above normal precipitation during December. The Wabash River was in flood and the Tennessee and Cumberland Rivers had sharp rises at the beginning of January.

Practically the entire month of January was characterized by a high pressure area located in the vicinity of Bermuda and another just west of the upper Mississippi River with a trough of low pressure midway between these two areas. The trough of low pressure extended in a southwest to northeast direction from eastern Texas to western Pennsylvania and varied very little from this position during the entire month.

This pressure distribution brought about a strong influx of warm, moist air from the Gulf of Mexico over the Ohio Basin. This warm, moisture-laden air over-ran a mass of cold air and was in contact with it from western Pennsylvania to eastern Texas. This resulted in heavy downpours of rain along the Ohio Basin and upper Mississippi River from Pittsburgh, Pa., to Memphis, Tenn.

The persistence of the high-pressure area over Bermuda prevented the eastward movement of the masses of air so that practically all of the excessive rainfall was confined to the Ohio Valley and lower Mississippi River. Some precipitation fell on the 1st and 2nd but the heavy rains began on the 7th and continued almost without interruption up to the 25th.

The heaviest daily rains occurred during the 24 hour period ending 8 a. m. of the 21st and the 22nd. Amounts reported from a few points are as follows: Little Rock, Ark., 4.36 inches on 21st; Memphis, Tenn., 3.24 inches, 22nd; Cairo, Ill., 2.92 inches, 21st, and Evansville, Ind., 2.78 inches, 21st.

The greatest 48-hour amounts occurred on the 21st-22nd and some of the amounts are as follows: Little Rock, Ark., 6.69 inches; Louisville, Ky., 5.82 inches; Cairo, Ill., 4.98 inches; Memphis, Tenn., 4.76 inches; Evansville, Ind., 4.30 inches, and Cincinnati, Ohio, 3.98 inches.

The total amounts of precipitation for the month up to 8 a.m. of the 25th for the same points are as follows: Little Rock, Ark., 16.91 inches; Memphis, Tenn., 17.17 inches; Cairo, Ill.,14.82 inches; Evansville, Ind., 14.24 inches; Louisville, Ky., 18.58 inches; Cincinnati, Ohio, 13.45 inches; Nashville, Tenn., 13.47 inches, and Pittsburgh, Pa., 6.56 inches.

With this excessive amount of precipitation falling on well-saturated ground, and extending along the Ohio Basin and lower Mississippi River from Pittsburgh, Pa., to Memphis, Tenn., the Ohio River began a steady rise along its entire length extending into the lower Mississippi below the confluence of the two streams. The tributaries of the Ohio, especially the Wabash, the Tennessee, and the Cumberland were in flood stage the first part of the month. The Wabash and the White Rivers in Indiana reached record breaking proportions.

By the 10th the lower Ohio River began exceeding the flood stage at

Evansville, Ind., and Cairo, Ill., and on the 19th the river was flooding over its entire length from Pittsburgh, Pa., to Cairo, Ill. The all time record of 71.1 feet at Cincinnati, Ohio, which occurred on February 14, 1884, was broken in the early morning of the 23rd. The river then rose steadily beyond this point until on the morning of the 26th the water had risen to the almost unbelievable height of 80 feet, which is 28 feet above the flood stage. All previous records were broken along the Ohio River from slightly below Parkersburg, W. Va., to the mouth, and the discharge from the Ohio River was rapidly being felt at Memphis, Tenn., where a stage of 42.7 feet on the morning of January 26, 1937, was within 3.9 feet of the all-time-record at that place.

In these floods snow was not a serious factor, but very often it is. This is particularly the case if a considerable depth of snow has accumulated and a spell of very warm weather, accompanied by rain, occurs. Even then the floods ordinarily do not become serious unless the rainfall is fairly heavy. In other words, what is needed is the accurate and timely forecasting of rainfall, particularly in regions where rivers are small and of fairly steep slope, and therefore where the floods are what are called of the "flashy" type. The question, therefore, arises as to what is being done in improving the short period forecasts of rain.

Since the World War quite definite progress has been made in the science of forecasting the weather. Prior to that time, methods were largely empirical and were based almost exclusively on observations of surface conditions and clouds. Later, however, with the introduction of the Bjerkness cyclone model, with its warm sector, bounded by the warm front and the cold front which meet near the center of lowest pressure in the cyclone, it was possible to explain by the application of well known physical laws the occurrence of most of our usual types of precipitation. In more recent years with the increase in the number of observations by airplane, it has been possible to obtain the characteristic properties with respect to temperature, humidity, pressure, of the masses of air which overlie great regions of our country from time to time. Studies of these air masses have permitted a clearer understanding of the inception of disturbances that affect our weather as well as the different kinds of precipitation which attend them. Further, it is possible from the plotting of airplane data on energy diagrams to determine the instability of the air and to ascertain the amount of lifting, either by thermal convection or by frontal action that is required to produce condensation. Such information becomes of great importance in the warm season in connection with the forecasting of thunderstorms. Formerly it was necessary to depend on the ability of the experienced forecaster to determine when and where a disturbance would originate and how rapid would be its development. From investigations of upper air data a great deal has been learned regarding the formation of fronts and the development of disturbances along these fronts. This permits estimates, having a greater degree of accuracy, as to when and where such developments will take place. Further, after a disturbance has once developed, recently devised kinematical methods with the help of the geostrophic wind scale, assist us in determining not only the direction and speed of movement of the disturbance but also whether it will increase or decrease in intensity.

It will be seen from the foregoing that although progress in forecasting is slow it is quite definite. We are confident that with further study of the increasing abundance of upper air data, secured by airplanes and other means, this progress will be very much greater in the next few years than during all the

previous history of meteorology. In this connection it is pertinent to state that the recent rapid development of the radiometeorograph, which, attached to a balloon and sending back signals of pressure, temperature and humidity, ascends to heights well above those attainable by airplanes, will undoubtedly result in a very great advance in our understanding of the atmosphere, and therefore in a marked improvement in forecasts of all types.

This brings us naturally to a consideration of the subject of long range forecasting. A great deal of study has been devoted already to the subject of seasonal, or longer, forecasts, especially with regard to cycles. The daily and annual cycles of temperature and, in a number of regions, the seasonal cycle of precipitation are the outstanding cycles of meteorological character. Others have such wide ranges in phase and amplitude that their usefulness in a practical way is quite problematical. Of course we know that weather records show rather definite trends upward in a general way for a number of years and then downward for a number of years. But the crests and troughs of such major variations recur with such varying and irregular periods that they have at most only a very general application; the reason being that they are so variable and that so many violent exceptions to the general tendency occur in individual years.

While the numerous methods that have been essayed have not produced particularly encouraging results, the benefits to be derived from forecasts covering a season or a year in the future are of such importance that they not only justify but urge further investigations in this field. Earnest efforts are being made along this line not only in this country but also in many others. In the Weather Bureau the problem has been taken up with special vigor during the past two or three years. Several lines of approach are being employed, including, in addition to cycles, correlations between pressure or other conditions in certain parts of the world and subsequent weather in the United States, and possible relationships between the variations in energy stored up in the oceans and the weather that follows in this country. As already stated, the results are not very encouraging as yet. The important point is that every possible effort is being made to determine whether or not usable bases or criteria for long range forecasts can be established.

In conclusion, a few words may be of interest as to plans and hopes for the future. As already stated, river and flood forecasting has in the past been in considerable part empirical in character. This was unavoidable during the pioneer stage. However, it is now possible and steps are being taken to put forecasting on a more rational basis. In these efforts special investigations are being made of the relation between rainfall and run-off, and therefore between rainfall and the occurrence of floods. In order to bring these improvements about, reorganization of the river and flood service of the Weather Bureau is proceeding along the following lines as rapidly as funds permit:

(1) The establishment of more and better placed rainfall stations, especially in head-water regions.

(2) The installation of an adequate network of recording rain gages to enable the forecaster to know the intensity of the rainfall. At present most of the rain gages used in flood work are of the eye-reading, 8-inch type.

(3) Surveys of the amount and condition of snow in the mountains, from which little information concerning snow is now available. Reliable and prompt

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rainfall reports are not sufficient when the mountain regions hold a great amount of water in the form of snow, which is likely to be released by the rain.

(4) Arrangements for a more reliable transmission of rainfall and river stage reports from the substations to the district centers. In the eastern floods of March 1936 the failure of wire communication was almost entirely responsible for any lack of timeliness and accuracy in the warnings issued. One suggestion is to establish radio stations in the flood producing regions and have them manned by Weather Bureau employees to transmit reports promptly under all conditions in order to avoid the possibility of a complete lack of information when wire communication breaks down. Another plan is to enlist the cooperation of amateur radio operators. Both of these suggestions are being studied with a view to determining some way in which the necessary data can be secured in all cases.

(5) Perhaps the most important feature of the reorganization is the division of the country into eight districts, each to be under the supervision of a hydrologic engineer, with a suitable staff of trained men. Under this plan each district center will be responsible for placing and supervising the operation of all substations, developing and putting into effect the transmission of reports to the forecasting centers, coordinating all phases of the work, including cooperation with other organizations, and developing formulas for forecasting. Through close cooperation with the Geological Survey discharge data are becoming available for all of the rivers of the country, and these data can be used to great advantage in combination with Weather Bureau data in the development of formulas that will bring about considerable refinement in the river stage and flood forecasts.

A beginning has been made in carrying out this general plan, two such district centers having been established at Davenport and Kansas City. It marks a definite departure from the practice of the past in that the men engaged in the work will be specialists therein, with no other duties. It is gratifying to be able to state that in those two districts the change has been received with enthusiasm by Army engineers engaged in flood control and other allied projects and by the representatives of all other agencies that have a part in this work.